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Estimation of uncertainties in CT metrology by simulation

Hiller, Jochen

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hiller, J. (Author). (2011). Estimation of uncertainties in CT metrology by simulation. Sound/Visual production (digital)

Estimation of uncertainties in CT metrology by simulation

CT Audit
University of Padova, October 26th

Jochen Hiller

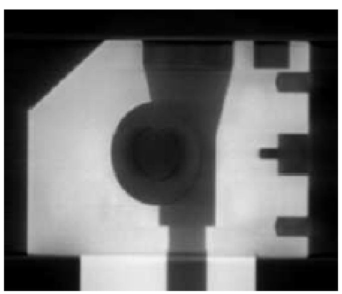
DTU Mechanical Engineering
Department of Mechanical Engineering

Content

- Motivation and problem definition
- The proposed approach
- Modelling and analytical simulation of CT scanning process
- Case study: Uncertainty estimation at a simple workpiece
- Summary and outlook

Motivation and problem definition

CT	Image processing	Coordinate measurement	Measurand
Reconstruction Image quality →	**Surface determination** →	**Coordinate measurement in 3D model** →	**Determination of dimension, form, and position**



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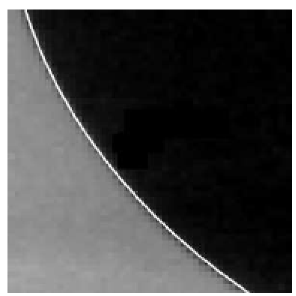

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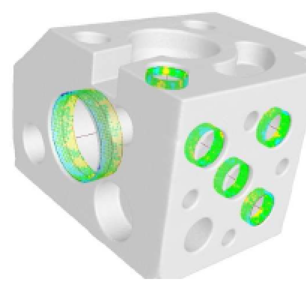

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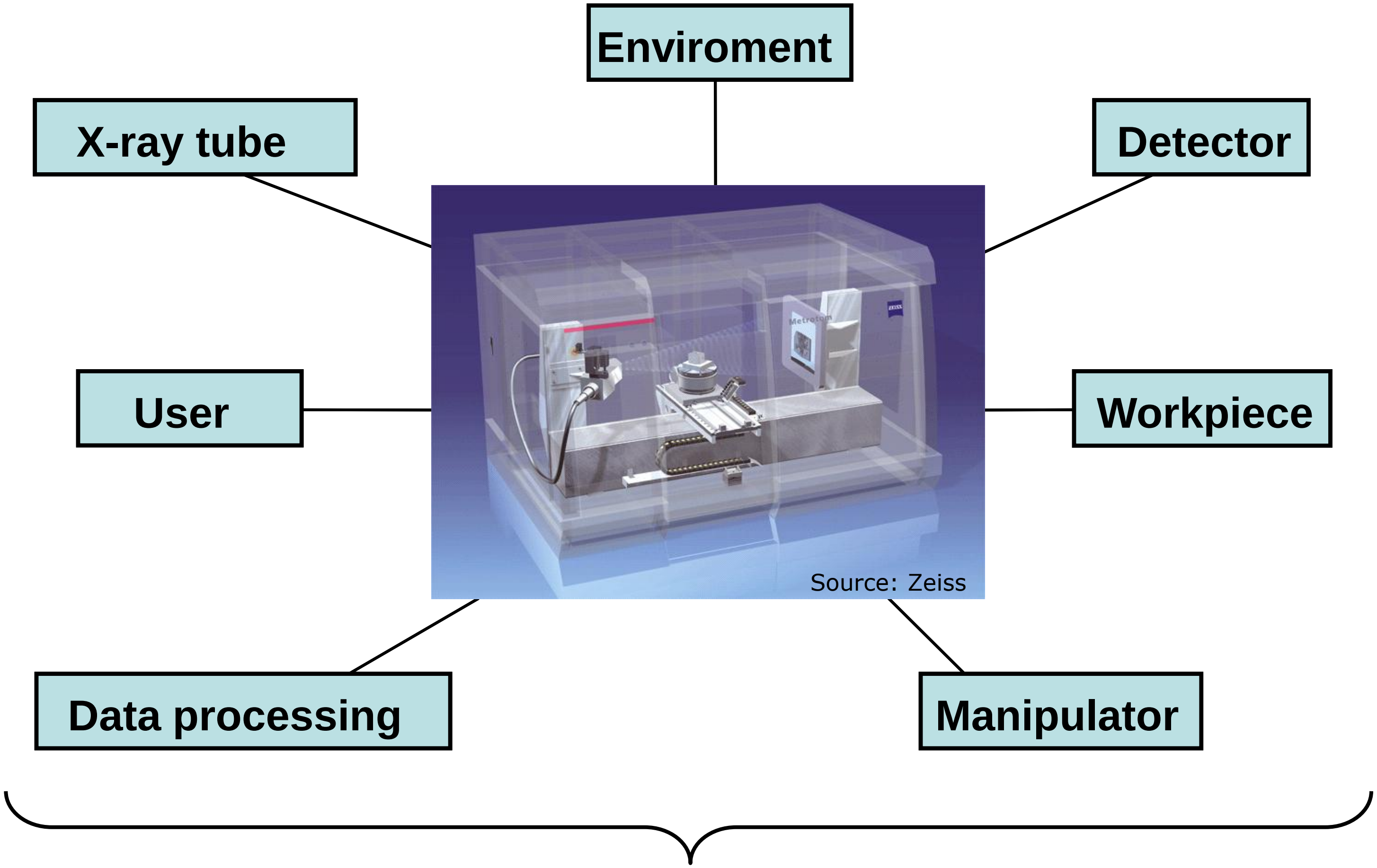
$\varnothing_1$ = 15,24 mm

$\varnothing_2$ = 18,87 mm

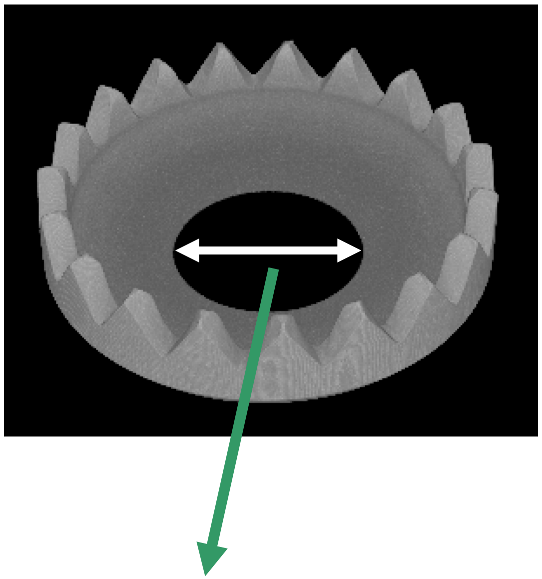
***Uncertainty*?**

Motivation and problem definition



Influences lead to systematic and random measurement errors

Motivation and problem definition



Ø: 2,424 mm ± ???

- **Analytical calculation**
  - almost not possible in CT
- **Experimental method**
  - calibrated workpiece available?
  - Destruction of the workpiece?
  - repeated measurements (time-factor)
- **Simulation method**
  - "virtual experiments" using computers
  - numerical evaluation of measurement uncertainty
  - Basis: Monte Carlo method (MCM)

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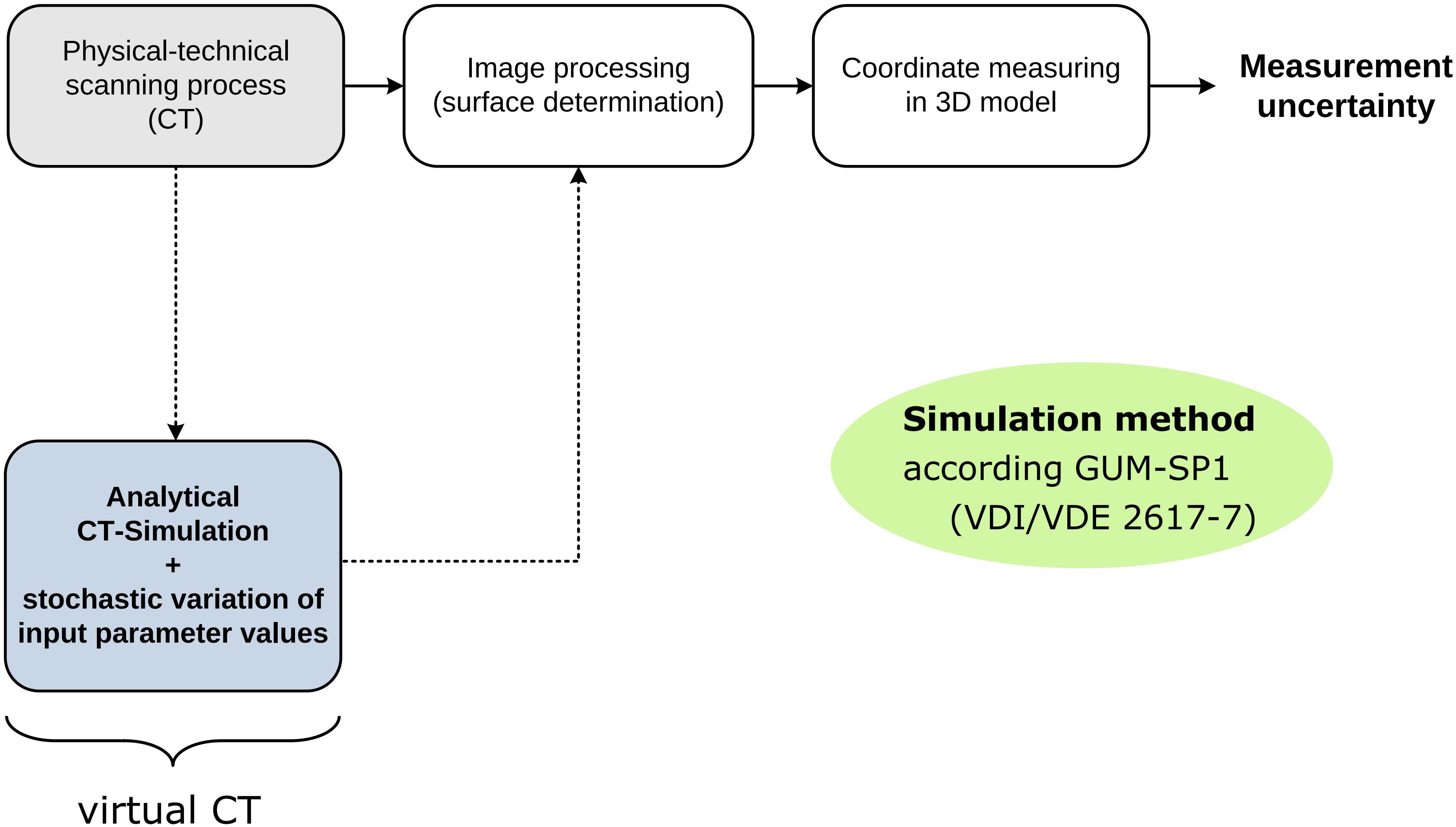
The proposed approach



Simulation method
according GUM-SP1
(VDI/VDE 2617-7)

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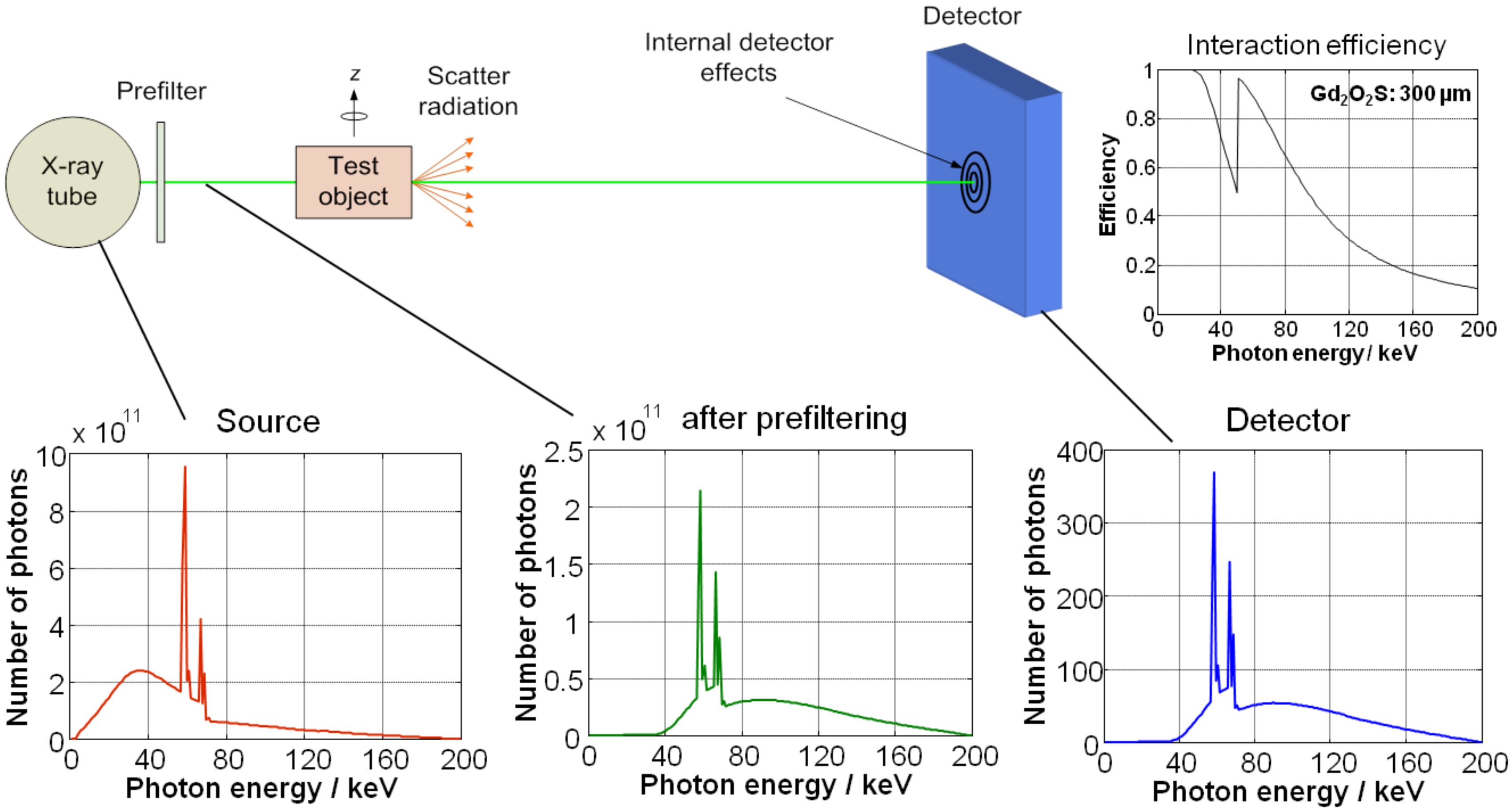
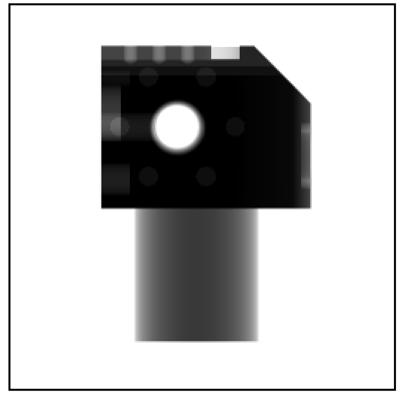
Modelling and analytical simulation

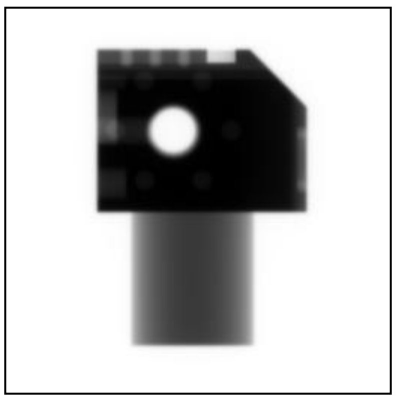


Modelling and analytical simulation



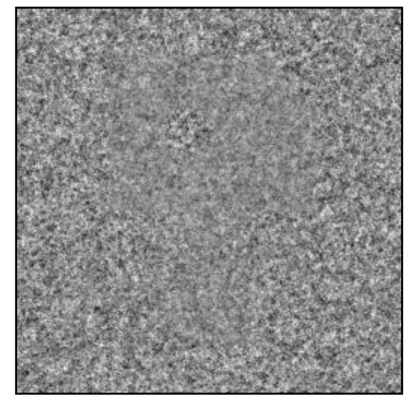
Expected pixel signal image

unsharpness

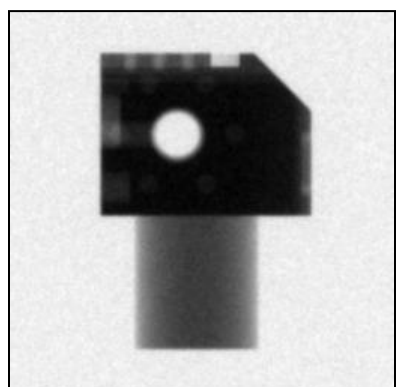


- Detector unsharpness
- Focal spot size & drift
- Object scatter radiation
- Detector/rotation axis misalignment
- Detector afterglow

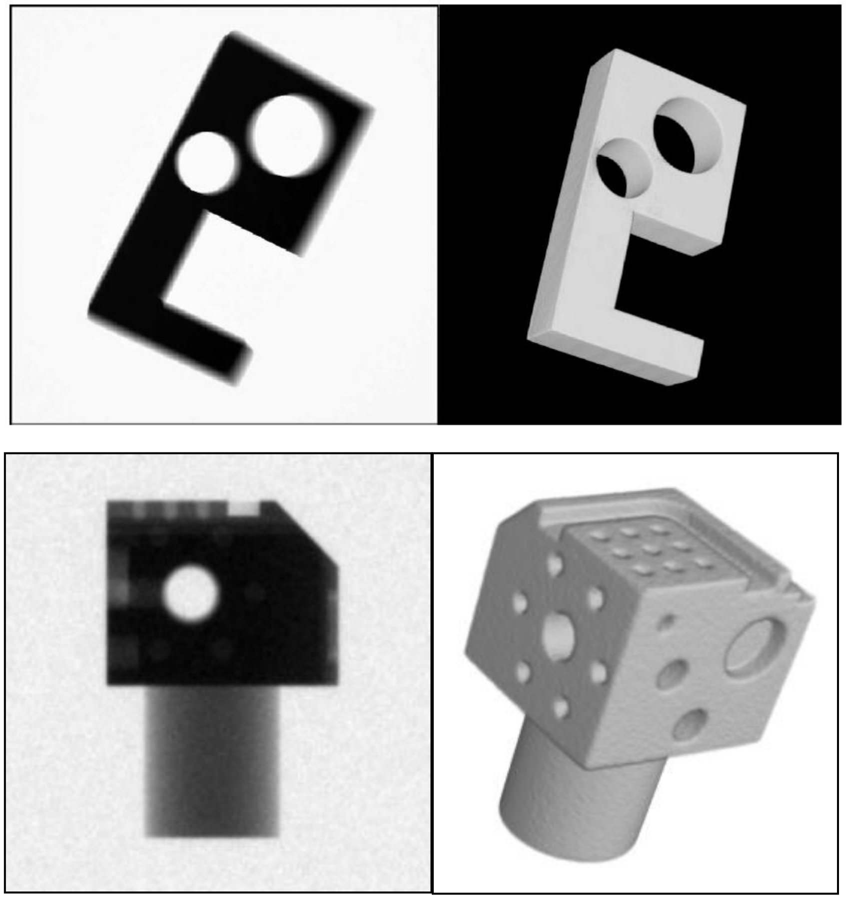
noise



Spatial variant & correlated image noise (quamtum + electronic)



Modelling and analytical simulation



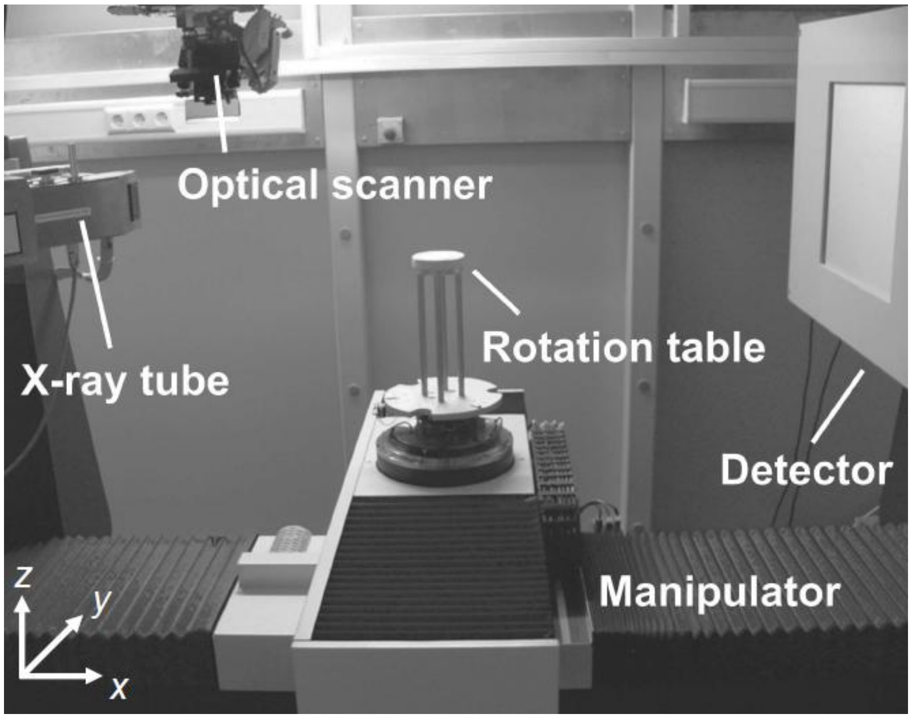
Projection CT model

- **Consideration of**
  - Image unsharpness
  - Image noise
  - Image artefacts (beam-hardening, scatter radiation)
  - System misalignment including temporal focus drift
  - Environment influences (temperature)
  - *Random variability of input quantities*

virtual CT

Modelling and analytical simulation

Tomolibri® Micro-CT system

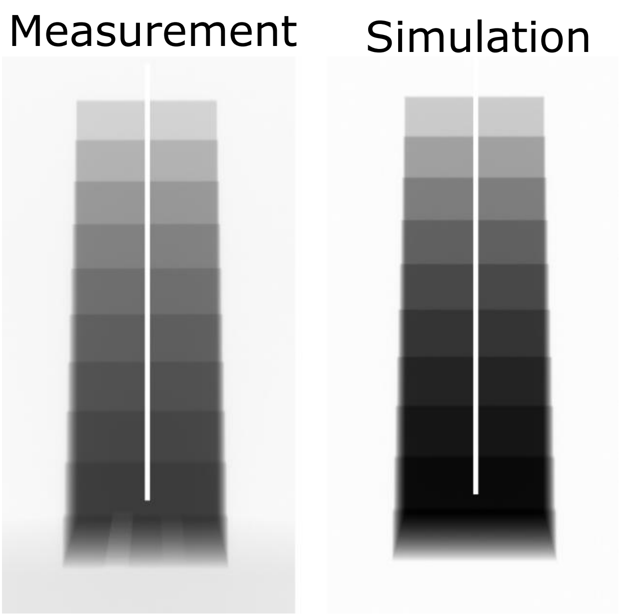


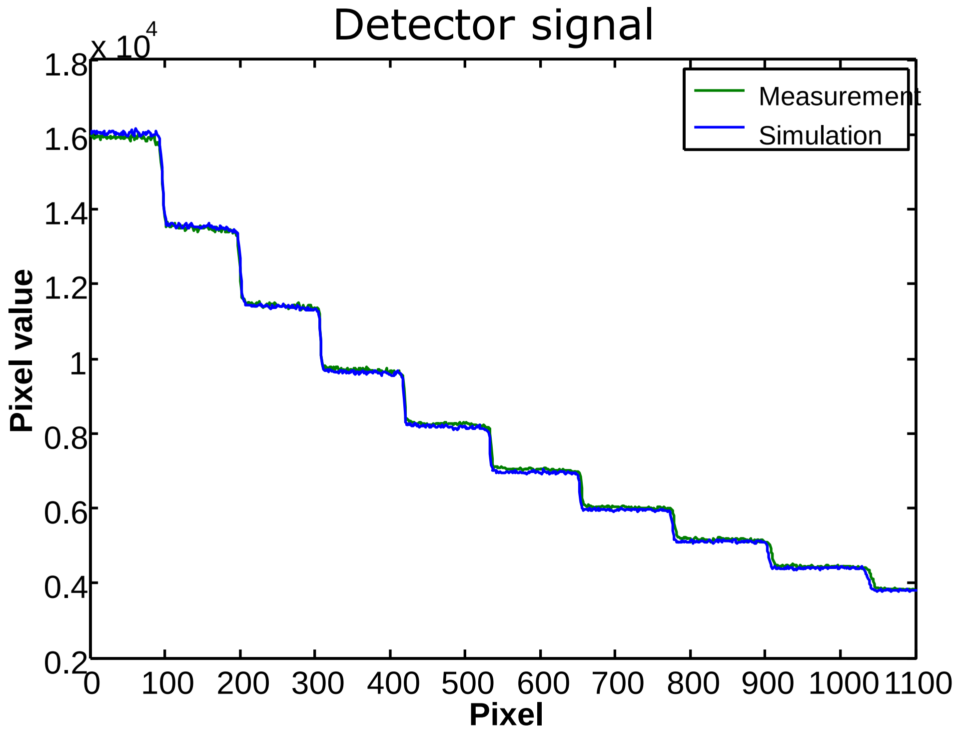
- **Relevant information**
  - Focal spot size
  - Focus drift
    (in 3 dimensions if possible)
  - Detector contrast & noise transmission
  - System misalignment parameters

By characterization measurements

Modelling and analytical simulation

First validation of synthetic projection images using simple test objects like step-wedges





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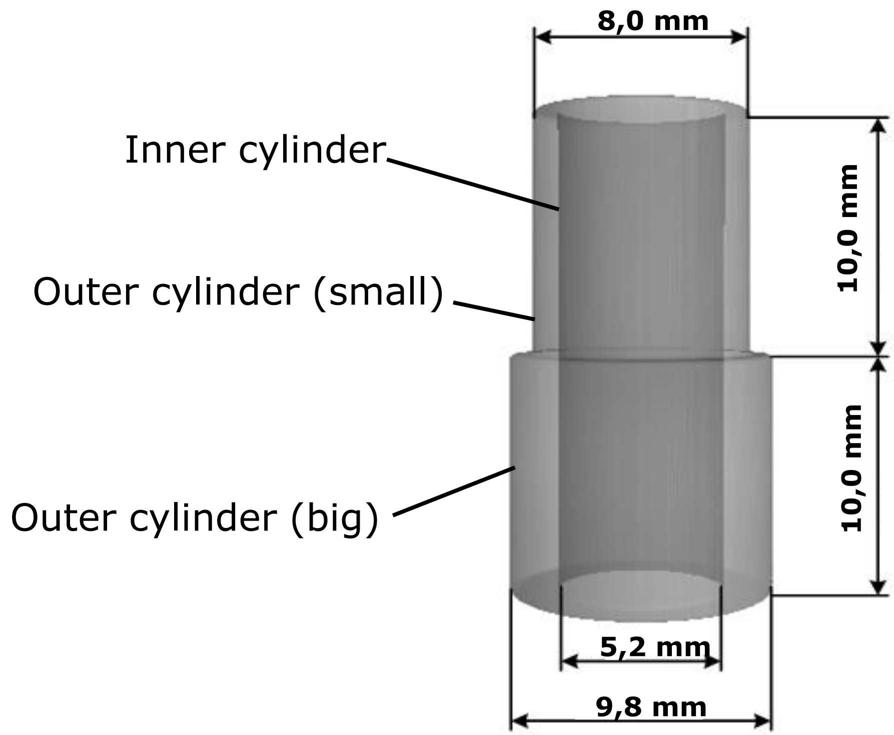
Case study

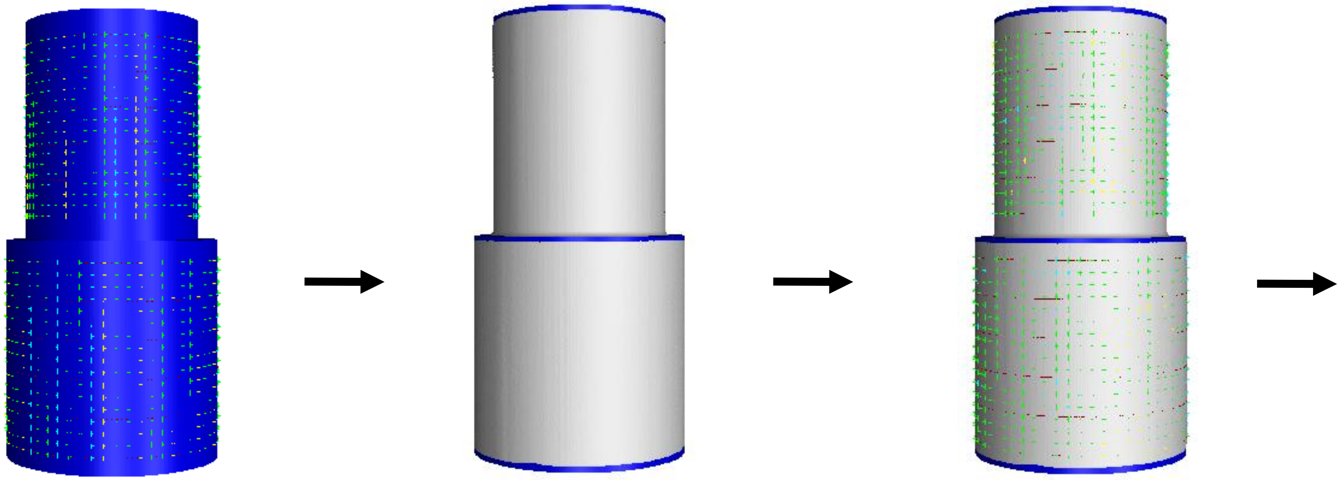
Material: X20Cr13 (Steel)



Measuring tasks:

- Evaluation of the 3 cylinder diameters
- Evaluation of associated form deviations of the cylindrical geometries

Case study



Result

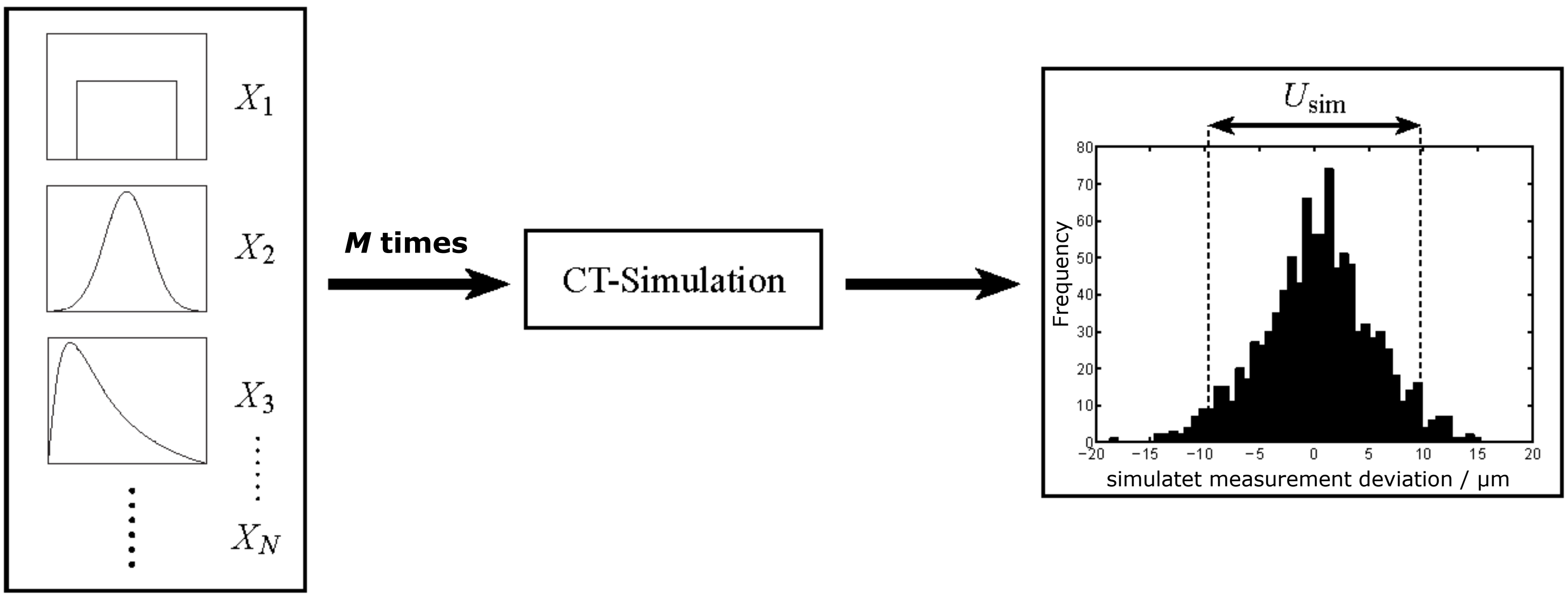
Measuring points on CAD model → Registration with CT model → Evaluation of spatial 3D coordinates & fitting → Result

<u>Result of dimensional CT measurements:</u>

Geometry element	Diameter in mm	Form deviation in µm
Outer cylinder, small	8,014	8
Outer cylinder, big	9,812	9
Inner cylinder	6,192	21

Case study

Stochastic variation of input parameter values



Input quantities **Model of CT** **Output quantity**

Case study

Parameter	Default	Uncertainty	Range of values
X-ray tube			
U_R	200	1 %	198 … 202
I_R	0,1	5 %	0,095 … 0,105
α_T	15,0	33,3 %	10,0 … 20,0
B_h	54,0	5 %	51,3 … 56,7
B_v	50,0	5 %	47,5 … 52,5
D_{h_1}	$8{,}45 \cdot 10^{-3}$	42,0 %	$(4{,}9 \ldots 12{,}0) \cdot 10^{-3}$
D_{h_2}	2,85	19,3 %	2,3 … 3,4
D_{v_1}	$4{,}03 \cdot 10^{-3}$	20 %	$(3{,}2 \ldots 4{,}8) \cdot 10^{-3}$
D_{v_2}	1,95	18 %	1,6 … 2,3
Geometry			
Δx_{det}	0,0	0,2 Pixel	−40,0 … 40,0
Δy_{det}	0,0	0,2 Pixel	−40,0 … 40,0
η_{det}	0,0	0,1°	−0,1 … 0,1
ϕ_{det}	0,0	1,0°	−1,0 … 1,0
θ_{det}	0,0	0,5°	−0,5 … 0,5
FDA	1539,447	1 %	1524,052 … 1554,841
FOA	114,953	0,3 %	114,608 … 115,298
Position			
T_x	0,0	0,5 mm	−0,5 … 0,5
T_y	0,0	0,5 mm	−0,5 … 0,5
T_z	0,0	0,5 mm	−0,5 … 0,5
R_x	0,0	1,5°	−1,5 … 1,5

U_{ct}

Uniform distributed input quantities assumed

Number of simulations $M = 50$

Case study

Result: $U = U_{sim} = U_{ct}$

- If uncertainty contribution $u_1 \ldots u_i$ from other sources avaliable (hybrid):

$$U = k \cdot \sqrt{u_1^2 + \ldots + u_i^2 + u_{\mathrm{sim}}^2} \quad \text{with} \quad u_{\mathrm{sim}} = \frac{U_{\mathrm{sim}}}{k}$$

- If uncertainty contribution $u_{sim_1} \ldots u_{sim_j}$ from simulation can be seperated

→ *no correlations among single contributions* $u_{sim_1} \ldots u_{sim}$:

$$U = k \cdot \sqrt{u_1^2 + \ldots + u_i^2 + u_{\mathrm{sim}_1}^2 + \ldots + u_{\mathrm{sim}_j}^2}$$

Case study

Completed result:

$$Y = y \pm U$$

- Diameter:

Geometry element	*U* (95 %) in mm	*U* (99 %) in mm	*Y* (95 %) in mm	*Y* (99 %) in mm
Outer cylinder, small	0,080	0,086	8,014 ± 0,080	8,014 ± 0,086
Outer cylinder, big	0,102	0,108	9,812 ± 0,102	9,812 ± 0,108
Inner cylinder	0,064	0,066	6,192 ± 0,064	6,192 ± 0,066

- Form deviation:

Geometry element	*U* (95 %) in µm	*U* (99 %) in in µm	*Y* (95 %) in µm	*Y* (99 %) in µm
Outer cylinder, small	3	3	8 ± 3	8 ± 3
Outer cylinder, big	4	4	9 ± 4	9 ± 4
Inner cylinder	6	9	21 ± 6	21 ± 9

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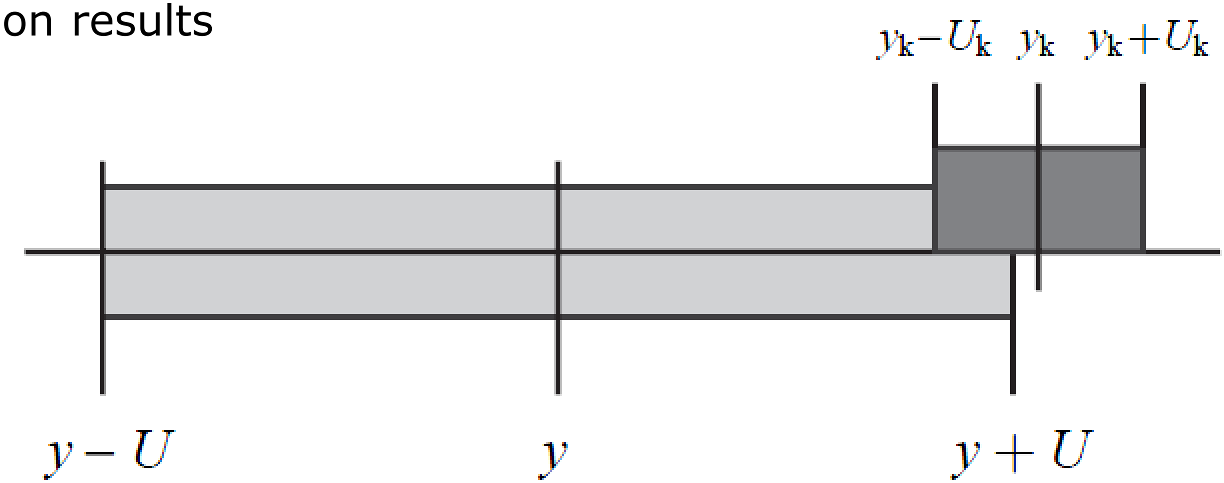
Summary and outlook

- *A simulation-based method to estimate uncertainties in dimensional CT using synthetic X-ray projection data and the Monte Carlo method, combined in the virtual CT, was presented*

- **Further developments should be concentrated on:**
  - Increasing of computational performance to increase the number of simulations
  - Development of systematic workflow for characterization of a CT system to adapt the simulation enviroment
  - Minimization of input quantities to the most significant ones and studying of correlations
  - Development of procedures to validate CT simulators in 2D/3D

Summary and outlook

- Usage/development of procedures to validate the simulation results



Test of plausibility according to VDI/VDE 2617-7

using calibrated workpieces:

$$|y_k - y| \leq (U_k + U)$$

calibrated value **measured value** **Calibration uncertainty** ***Uncertainty by simulation***

Thank you for your attention